

# DSMC simulations of the Shuttle Plume Impingement Flight EXperiment (SPIFEX)

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DSMC17  
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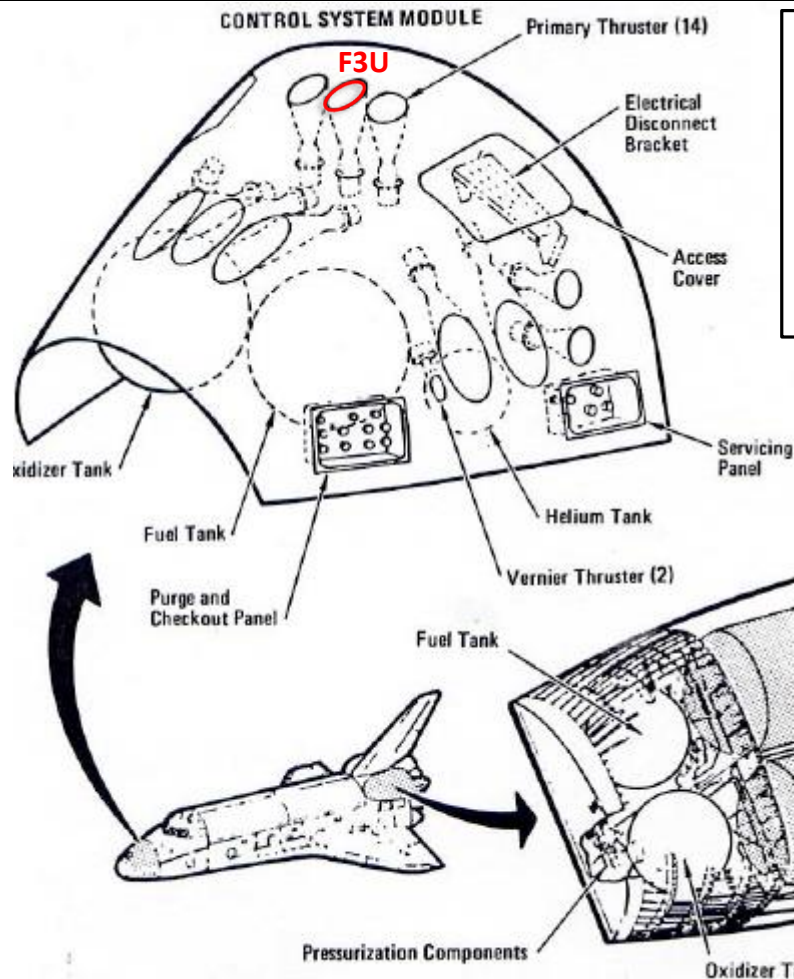
# Background



- During orbital maneuvers and proximity operations, a spacecraft fires its thrusters inducing plume impingement loads, heating and contamination to itself and to any other nearby spacecraft
- These thruster firings are generally modeled using a combination of Computational Fluid Dynamics (CFD) and DSMC simulations
- The Shuttle Plume Impingement Flight EXperiment (SPIFEX) produced data that can be compared to a high fidelity simulation
  - Due to the size of the Shuttle thrusters this problem was too resource intensive to be solved with DSMC when the experiment flew in 1994
- **Objective:**
  - Run DSMC Analysis Code (DAC) simulations of specific SPIFEX flight test data points
  - Compare the DAC pressure and heating data to the SPIFEX test data



# Shuttle RCS Thrusters



38 Primary Thrusters (14 Forward, 12 per Aft Pod)  
Thrust = 870 lbs  
6 Vernier Thrusters (2 Forward, 2 per Aft Pod)  
Thrust = 24 lbs  
Propellants:  $N_2O_4$  and MMH

Reaction Control System

ATI

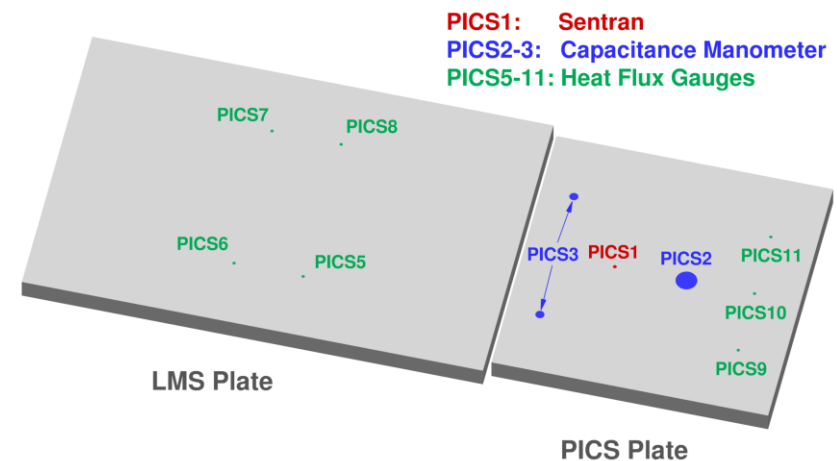
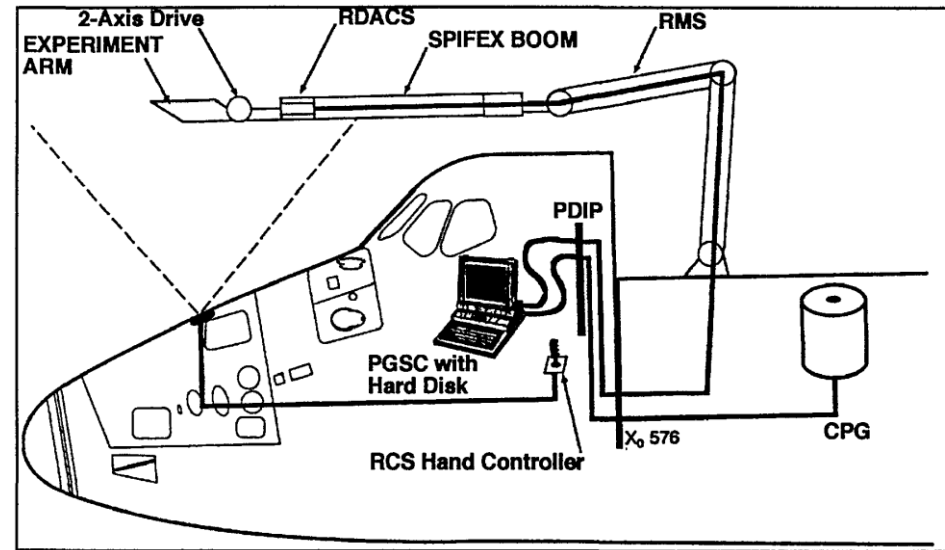
<https://www.slideshare.net/atcourses/fundamentals-of-rockets-missiles>



# Shuttle Plume Impingement Flight Experiment (SPIFEX)



- Flew on STS-64 (Sep. 1994)
- Plate with pressure and heat rate sensors attached at the end of a boom moved around by the Shuttle robotic arm
- Around hundred test points using multiple thruster combinations
- Simulated test points:
  - F3U -> Cover range of locations in the plume (Centerline versus high angles)
  - Norm-Z (F3U+L1U+R1U) -> Look at interaction zone between plumes





# Vacuum Thruster Plume Simulations



- Span several flow regimes from continuum inside the nozzle to transitional inside the near-field plume to free molecular in the far-field plume
- Currently cannot be modeled with a single solver but must instead use a multi-step approach:
  - Use a Computational Fluid Dynamics (CFD) solver in the continuum regions (GASP)
  - Interpolate the CFD solution at some interface to be used as input to the DSMC solution
  - Use a DSMC code in the rarefied regions (DAC)
- Use the Bird breakdown parameter to guide the interface location:
  - $$\mathbf{B} = 2 \frac{\mathbf{V}\lambda}{\mathbf{c}\mathbf{r}}$$
  - Interface located where the continuum assumption is valid
  - However, near edge of continuum validity such that DSMC simulation is not too computationally expensive



# SPIFEX Simulations



- NASA's DSMC Analysis Code (DAC)
  - Created to solve low density flows such as high altitude plume impingement flows and hypersonic reentry flows
  - Parallel, three dimensional code
  - 3D domain meshed using a 2-Level Cartesian grid
  - Use a multi step approach to resolve the flow field
  - Bodies represented using water tight triangulated surfaces
  - Written primarily in FORTRAN with small amount of C
  - Uses the Message Passing Interface (MPI) message passing scheme to effect communication between the processors
- SPIFEX simulations parameters:
  - Use nearest neighbor collisions
  - Target a cell size of 2 hard sphere mean free path
  - Target 10 molecules per cell

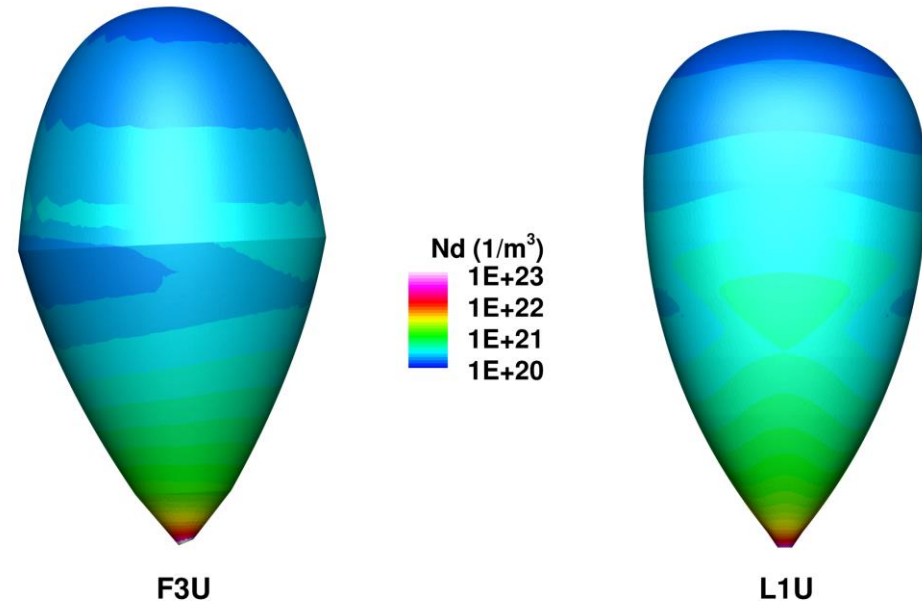




# DAC Input Conditions



- Nozzle and near field plume solved with the General Aerodynamic Simulation Program (GASP) CFD code
  - Chamber Pressure = 152 psi
  - 11 species ( $\text{CO}_2$ ,  $\text{H}_2\text{O}$ ,  $\text{N}_2$ ,  $\text{H}_2$ ,  $\text{O}_2$ ,  $\text{NO}$ ,  $\text{CO}$ ,  $\text{OH}$ ,  $\text{N}$ ,  $\text{O}$ ,  $\text{H}$ ) and 86 reactions
- Use a Bird breakdown parameter value of 0.03 to guide the interface location
- Surface data is scaled to match nominal mass flow rate and thrust (see Backup)
- Assume a single species with a molecular mass of 23.172 g/mol (centerline value in the CFD solution)

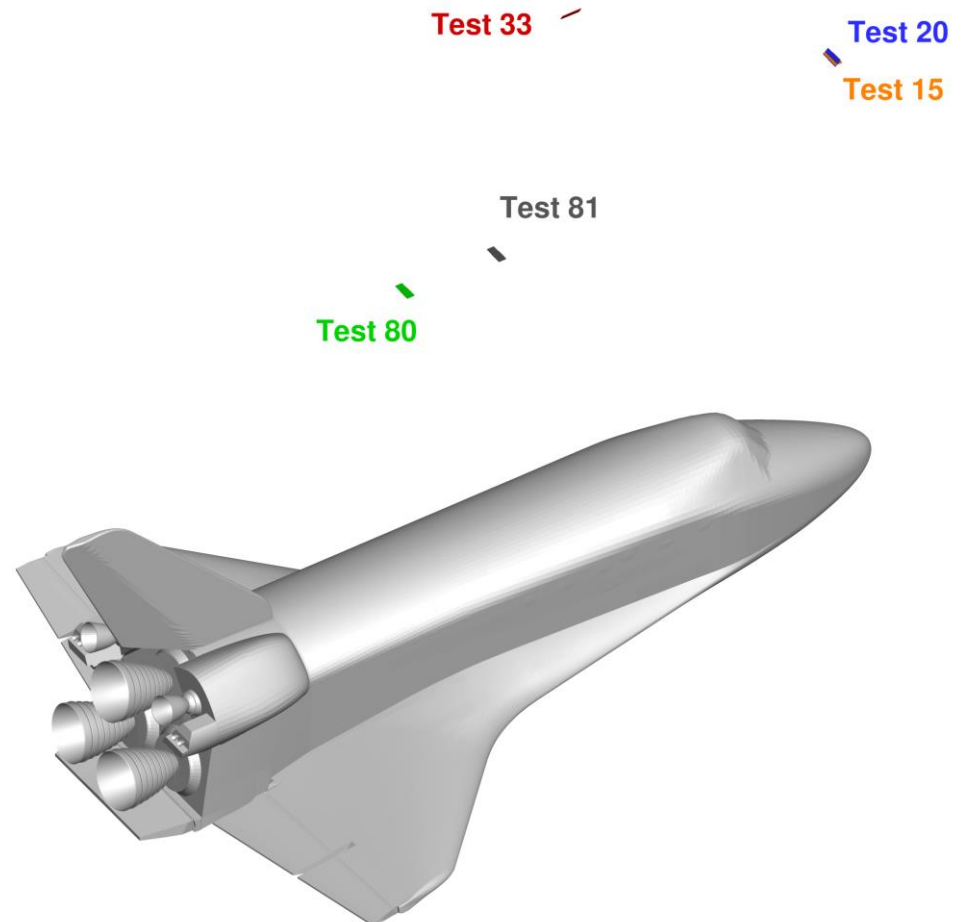




# Run Matrix



Test Case		Objective
F3U	15	Normal impingement along plume centerline
	20	Impingement at intermediate angle of attack along plume centerline
	33	Normal impingement at high angle off centerline
Norm-Z	80	Impingement near dual interaction region
	81	Impingement near triple interaction region



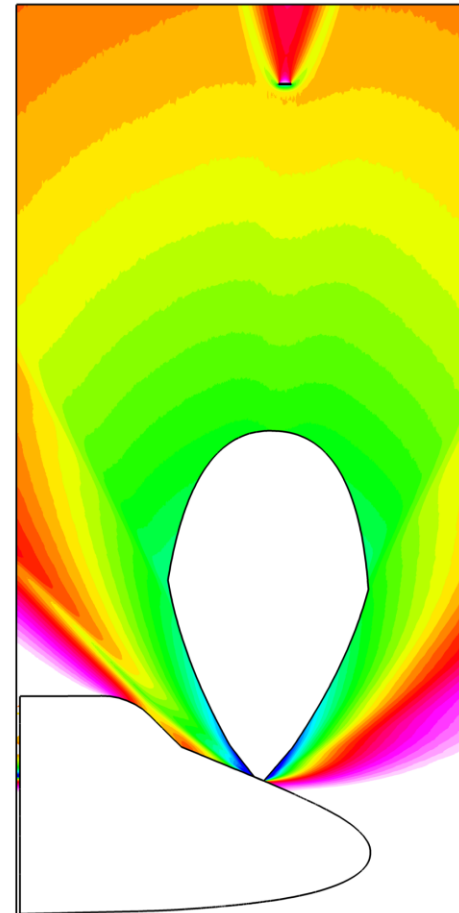




# Run Statistics



Test Case		Statistics
F3U	15	5.8B molecules 359M cells
	20	5.8B molecules 356M cells
	33	6.1B molecules 379M cells
Norm-Z	80	23.4B molecules 1.59B cells
	81	22B molecules 1.4B cells



Mean free path (m)

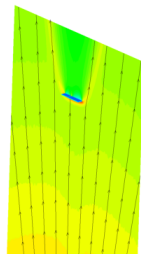
1.00E+00  
1.00E-01  
1.00E-02  
1.00E-03



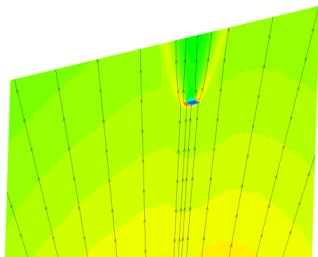
# F3U Test 15



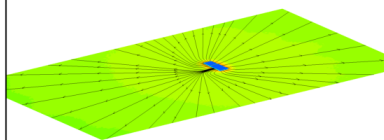
X = 8.25 m



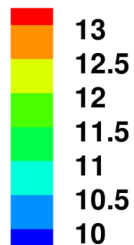
Y = 0.0 m



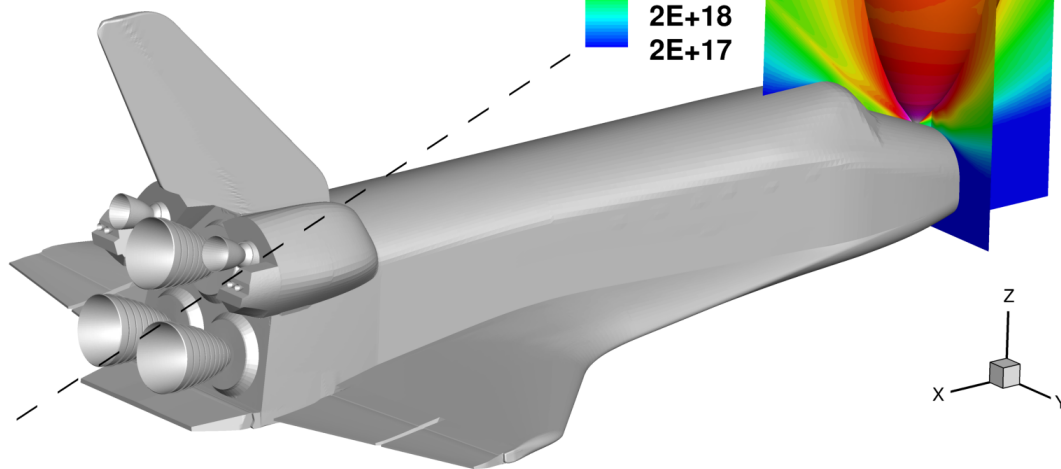
Z = 28.8 m



P (N/m<sup>2</sup>)



Nd (1/m<sup>3</sup>)

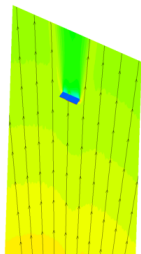




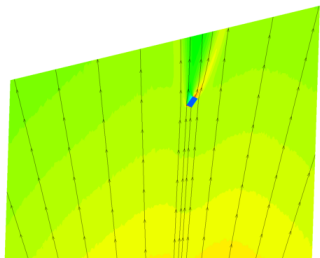
# F3U Test 20



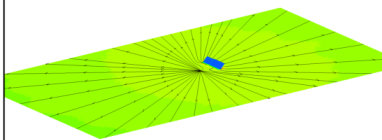
X = 8.25 m



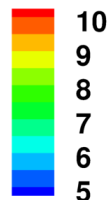
Y = 0.0 m



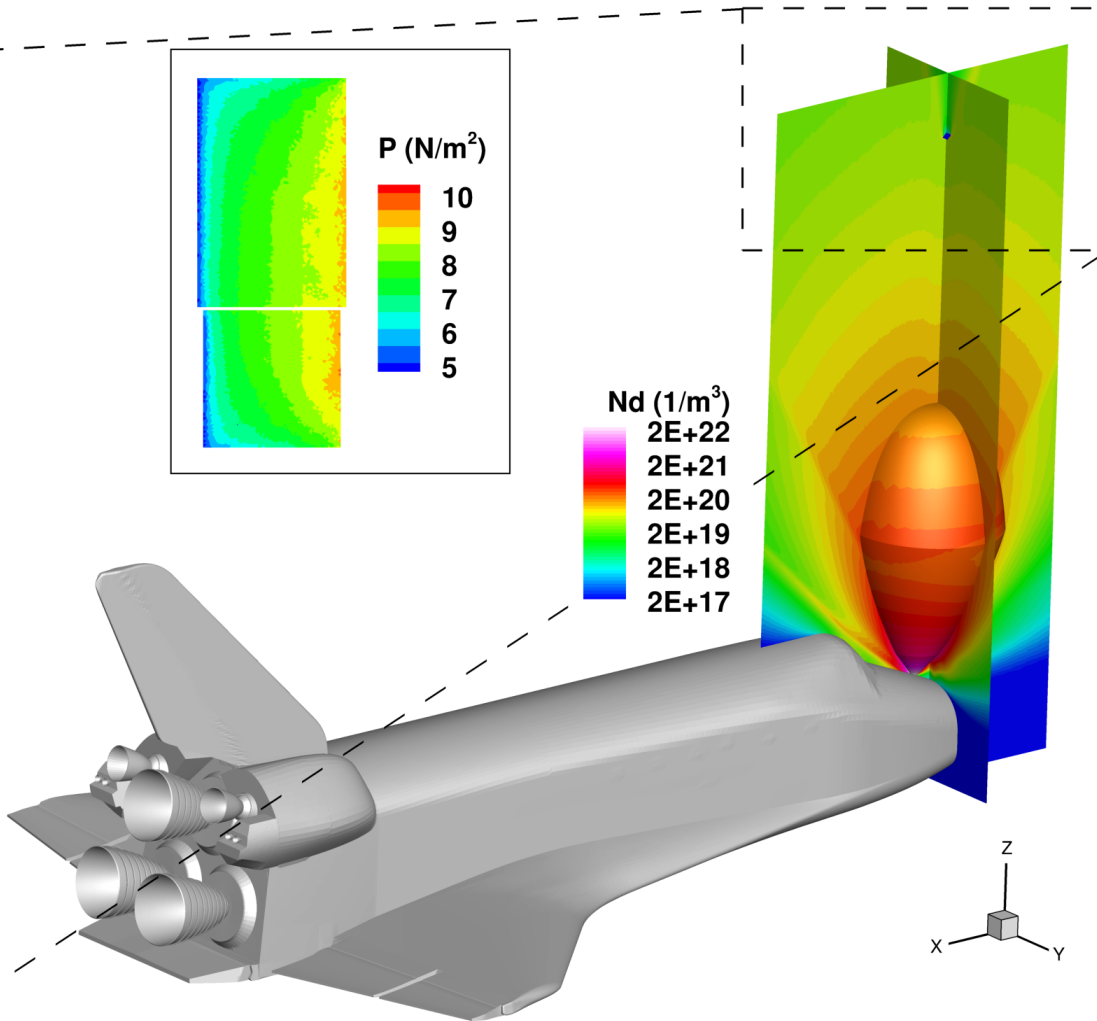
Z = 28.8 m



P (N/m<sup>2</sup>)

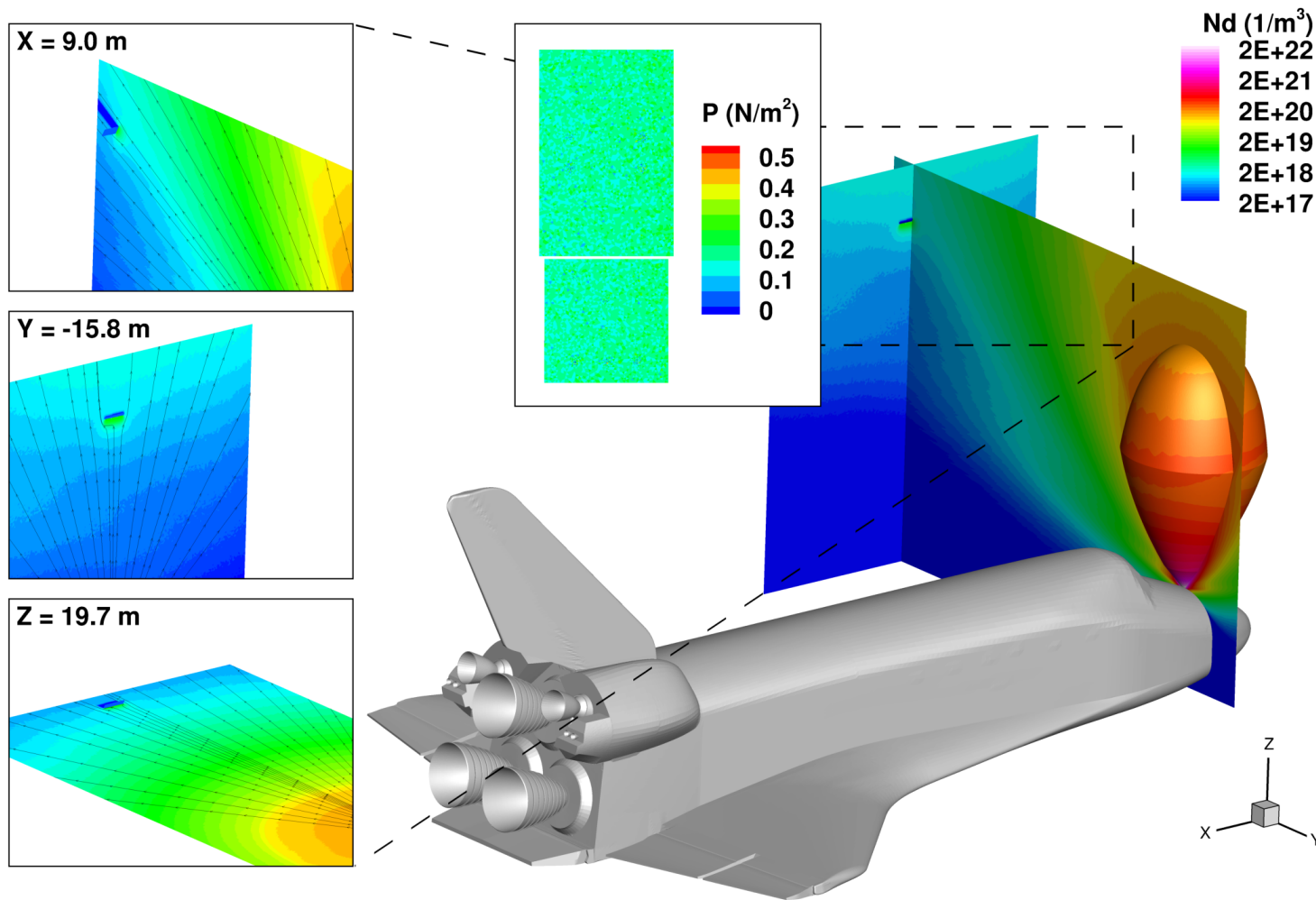


Nd (1/m<sup>3</sup>)



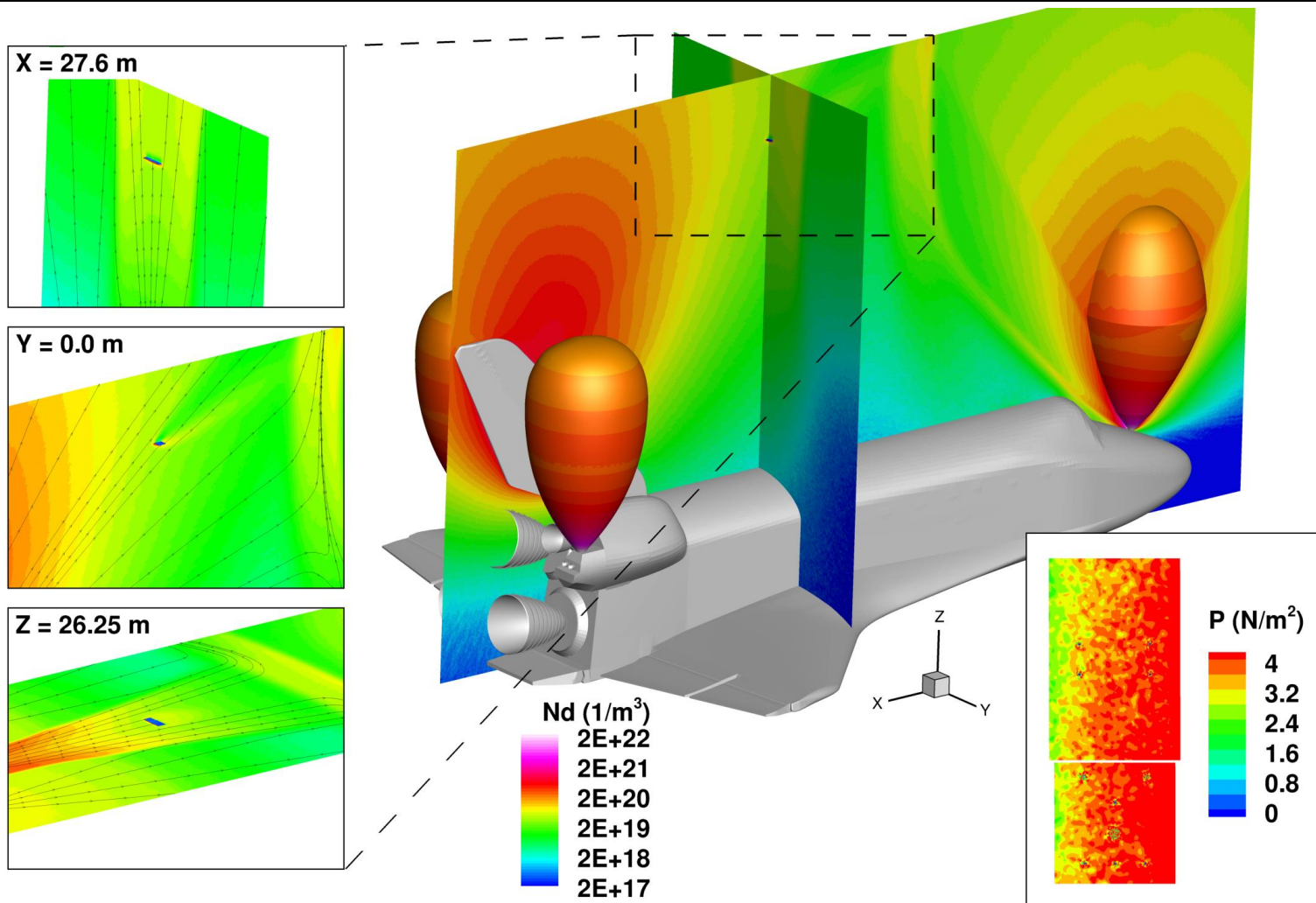


# F3U Test 33





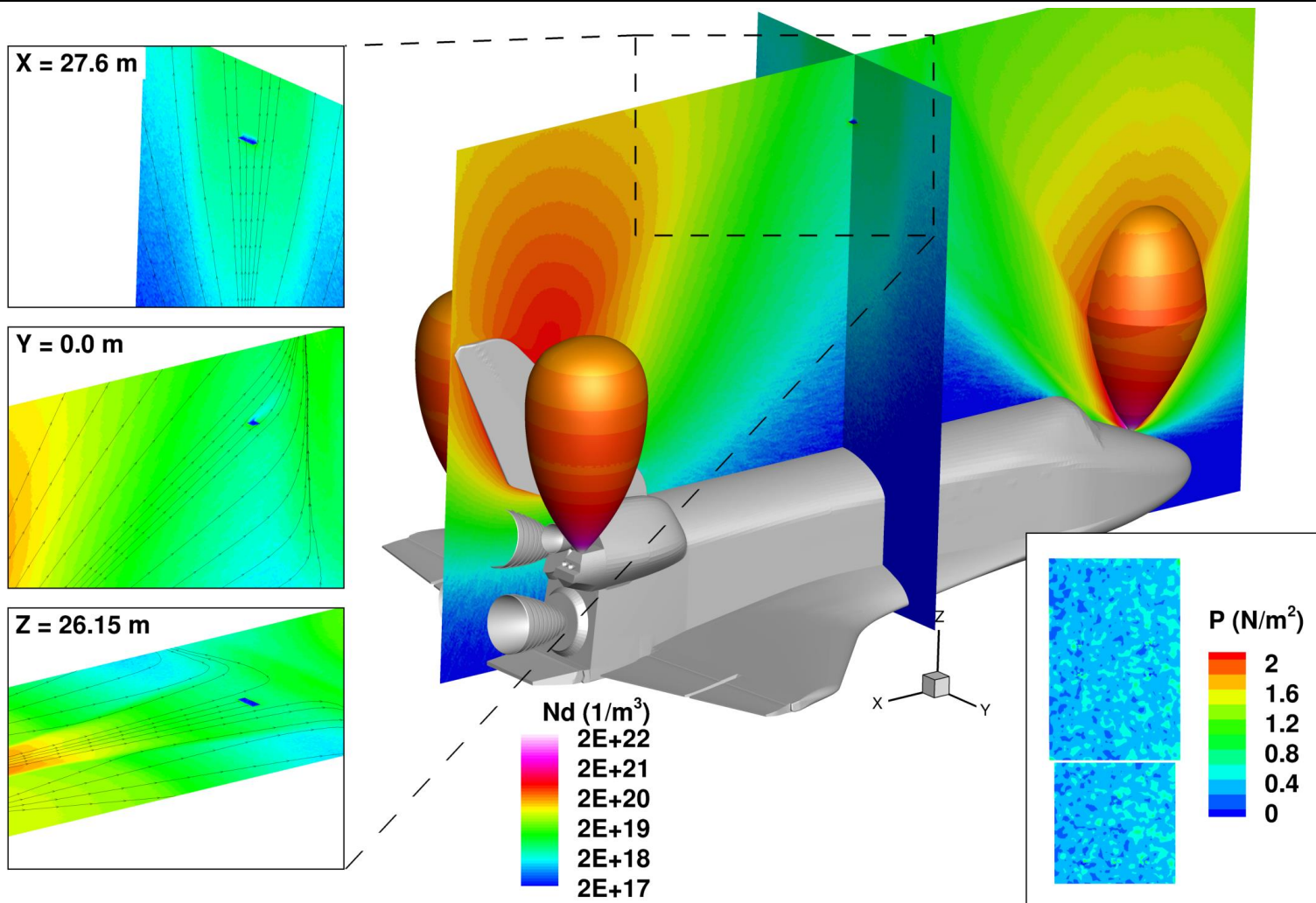
# Norm-Z Test 80







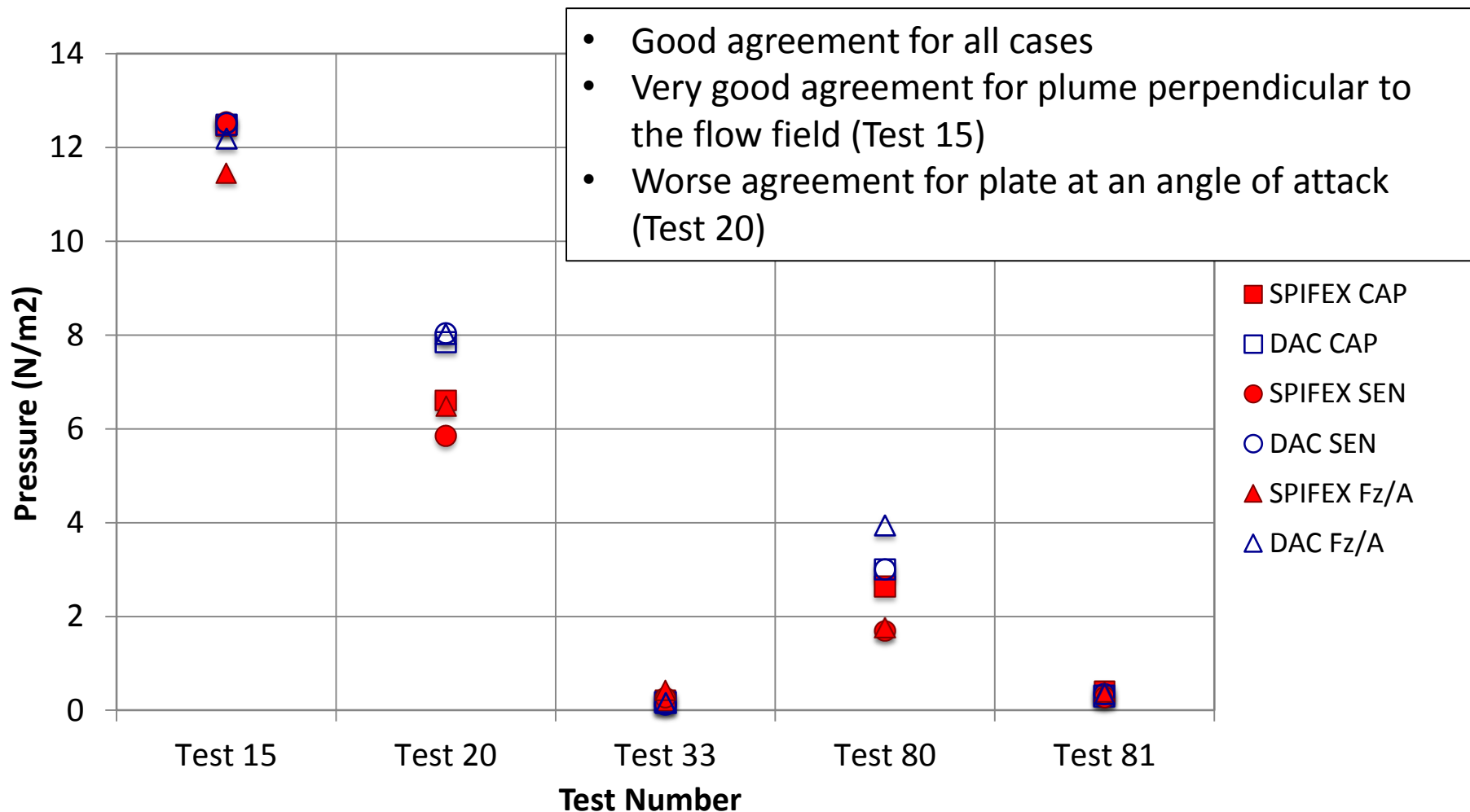
# Norm-Z Test 81





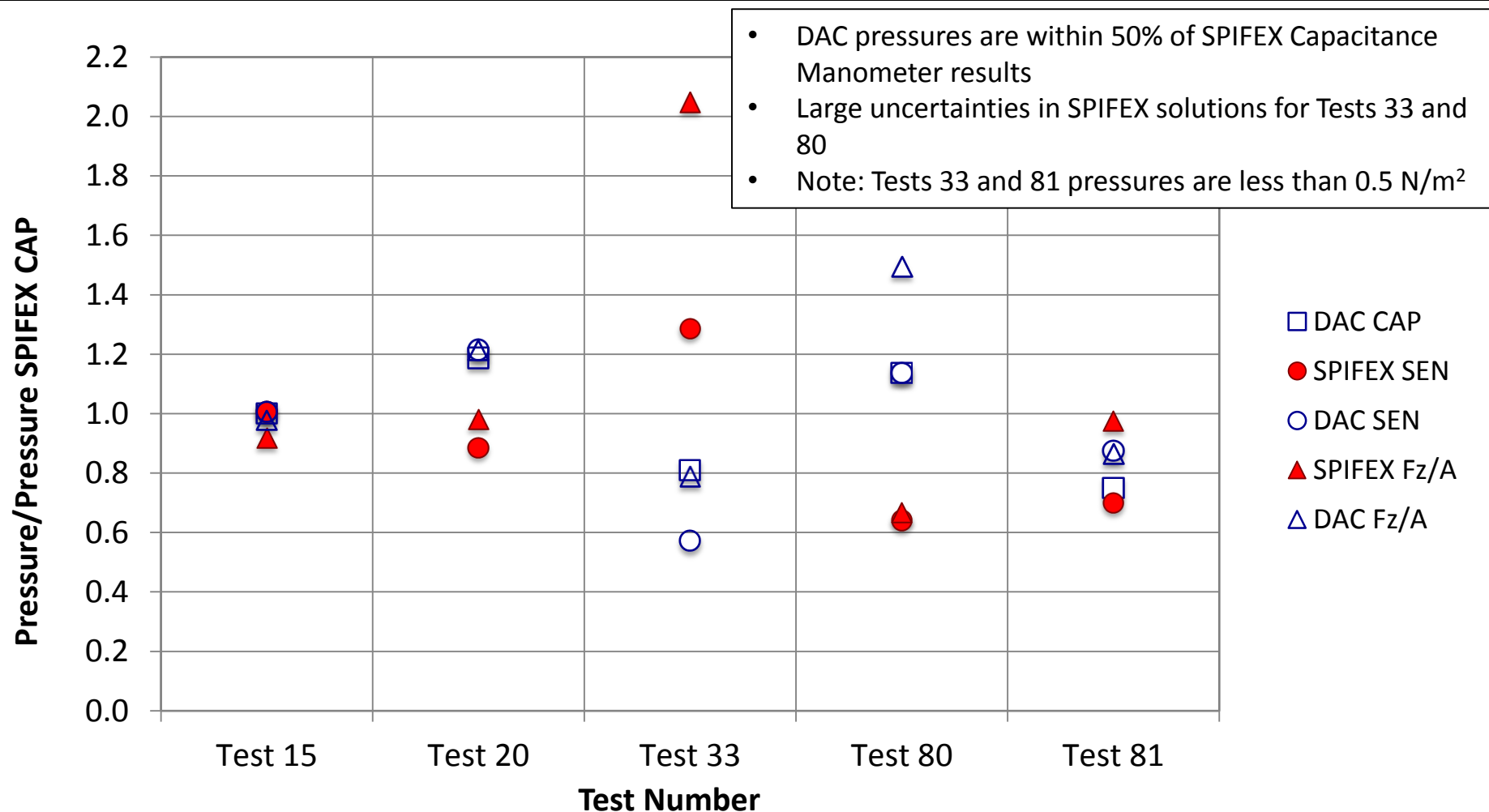


# Pressure Comparisons



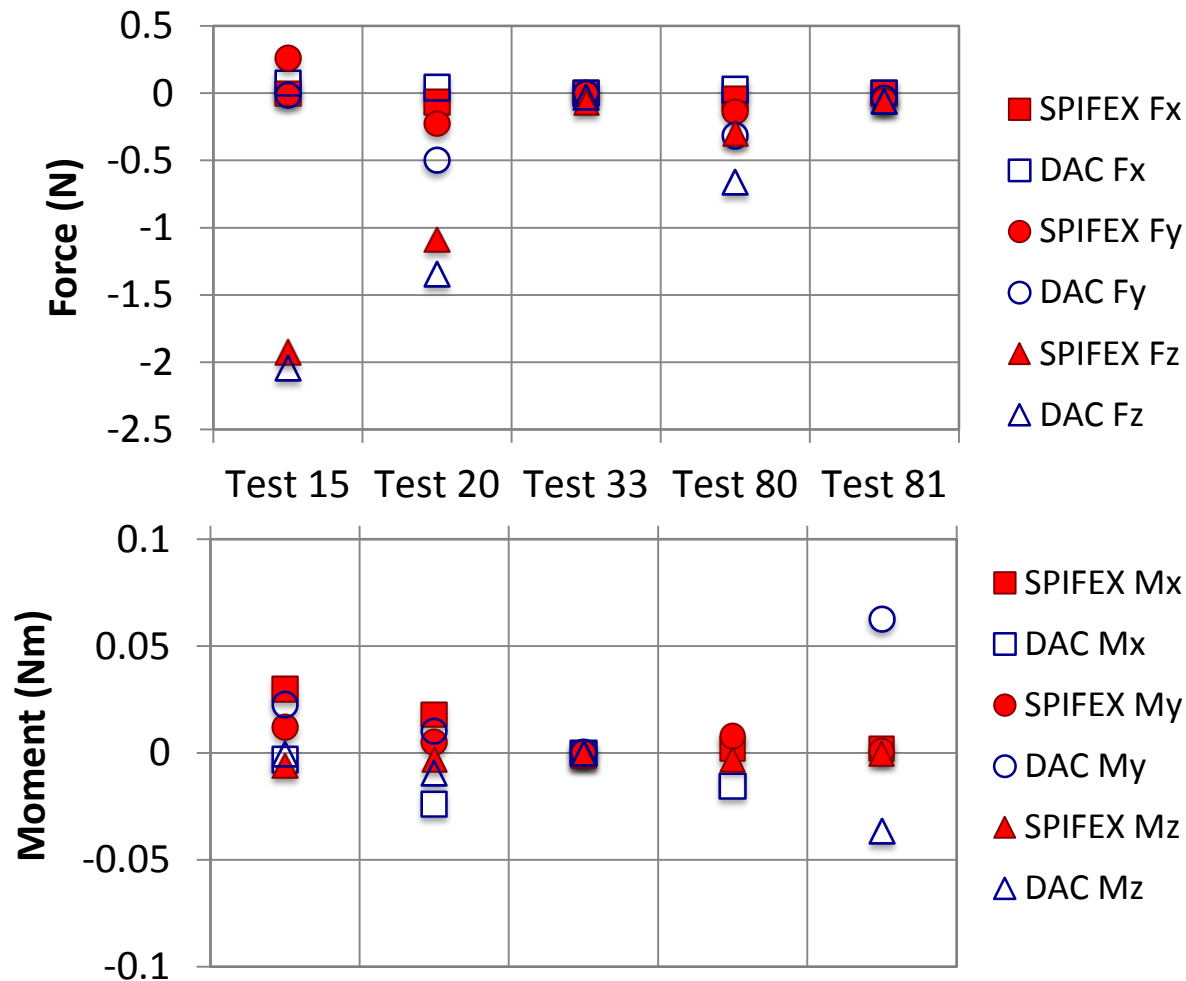


# Pressure Comparisons





# Forces and Moments on LMS Plate



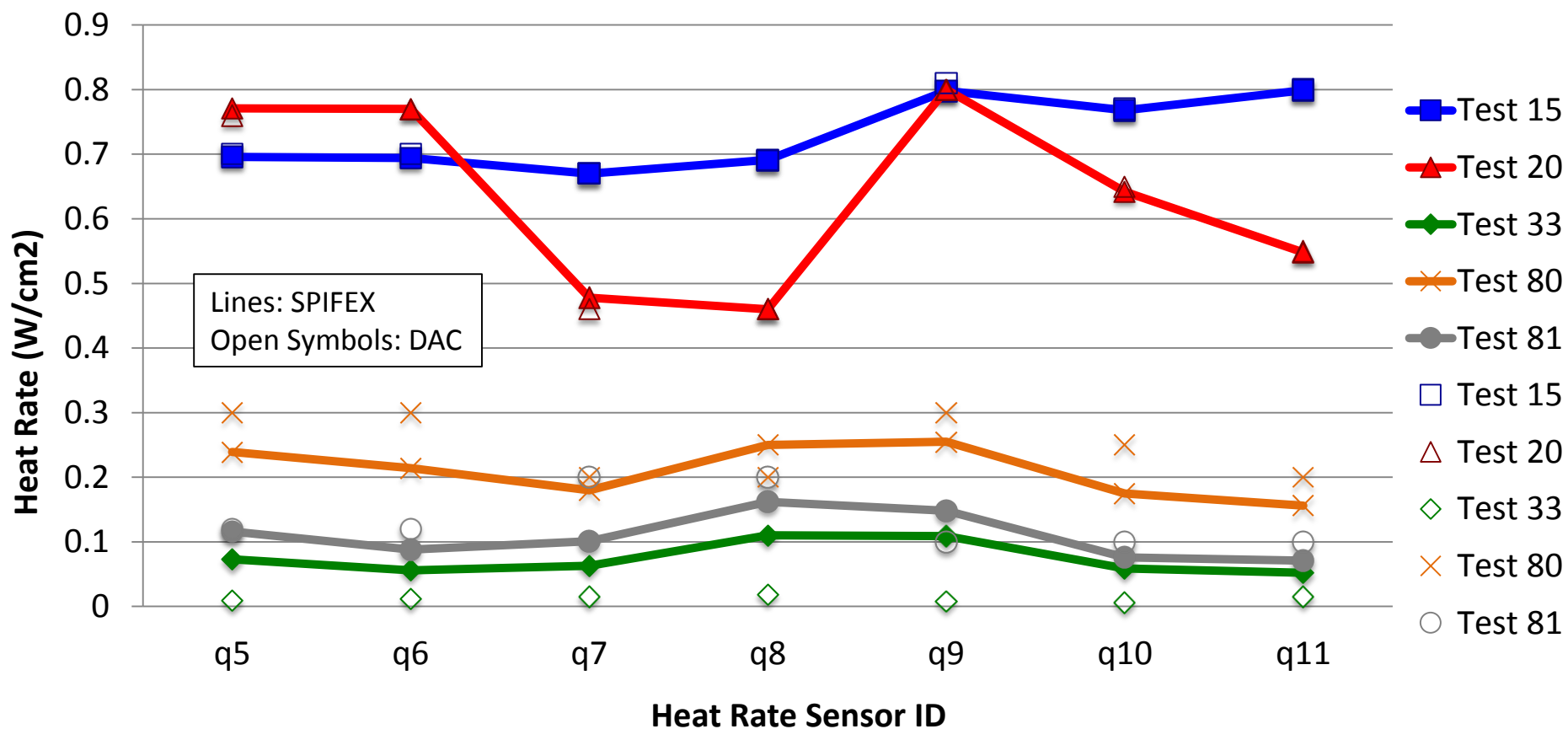
- Good agreement for largest force components for normal impingement
- Worst agreement for plate at an angle of attack (Test 20) and for Norm-Z cases (Tests 80 and 81)



# Heat Rates



- Very good comparison for high heat rate cases
- DAC underestimates the heat rates for the high angle off centerline case (Test 33)





# Summary



- F3U:
  - Good agreement for pressure, forces and moments for near normal impingement
  - Larger discrepancies for plate at angle of attack and high angle off centerline cases
  - Very good agreement for high heat rate cases
- Norm-Z:
  - Larger discrepancies between DAC and SPIFEX results
- Forward work:
  - Rerun the CFD simulation of the nozzle and plume near field
  - Add the OMS pods to the shuttle geometry being modeled in the Norm-Z simulations
  - Run multi species case in DAC
  - Run additional test data points
  - Do sensitivity study of the impact of changes in impingement angle

# Backup





# Scaling to Match Nominal Thrust and Mass Flow Rate



- Nominal Values:
  - Mass Flow Rate: 3.1 lbm/s
  - Thrust: 870 lbf
- Final values match the nominal values within 0.5%

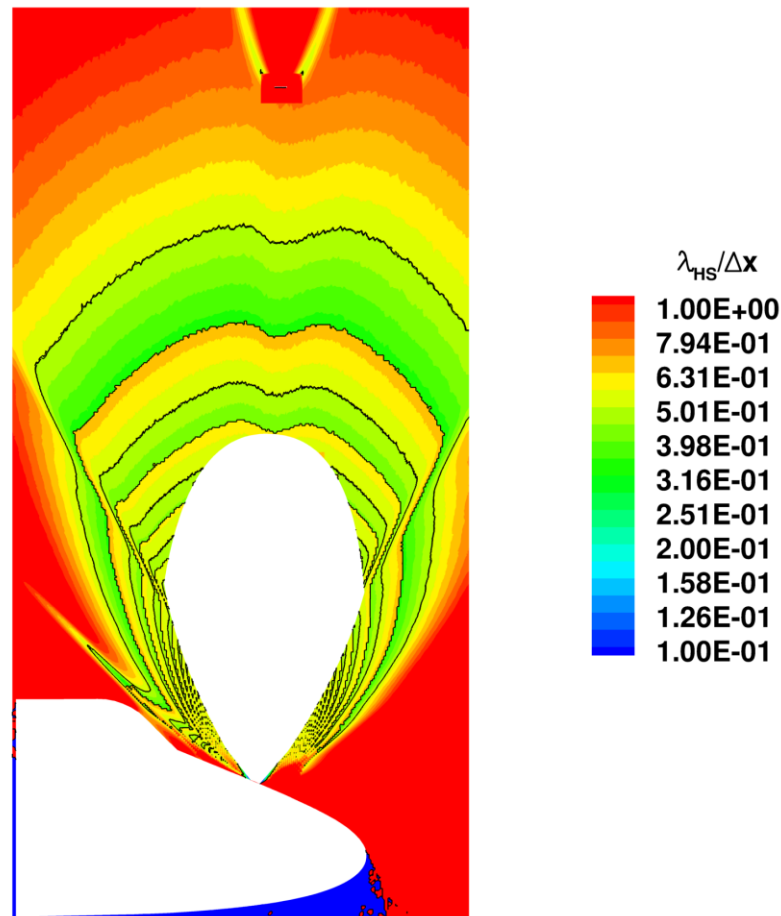
Thruster	F3U	L1U
Number Density Scaling	21.7%	17.2%
Velocity Magnitude Scaling	-7.7%	-6.6%



# Run Statistics



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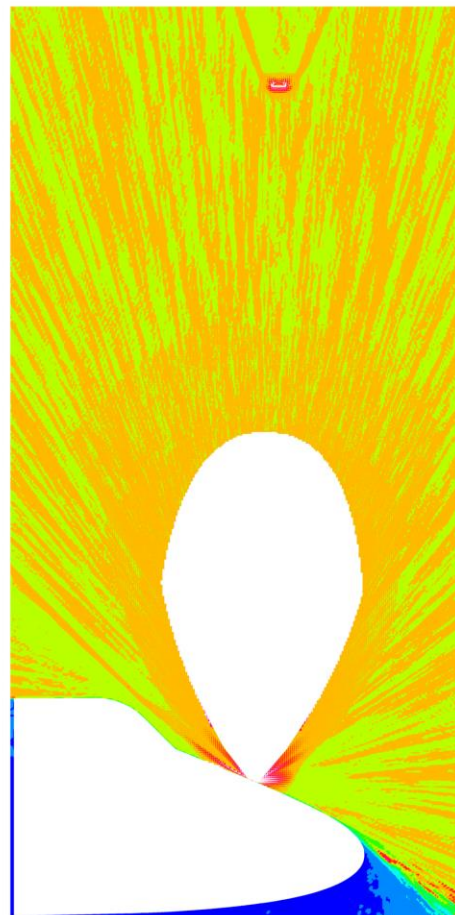




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Population

